CLAIMS

We claim:

1. An iterative method of normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:
   a) inputting a time domain measurement data set $D_{ji}^{d}(t), \quad (j = 1 \sim NG;\ i = 1 \sim NS)$, where d denotes a data tensor, NG is the number of receivers and NS is the number of sources;
   b) means for minimizing a model parameter $\boldsymbol{m}$ below an error bound in the process of creating a normalized waveform inversion, wherein said minimizing step further comprises:
      i) Fourier transforming the time domain measurement data set $D_{ji}^{d}(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$;
      ii) normalizing the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$;
      iii) modeling a medium by iterating the model parameter $\boldsymbol{m}$ describing one or more physical properties of the medium; by
         (1) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$ of the response of the medium, to a level below the error bound;
         (2) outputting the iterated model parameter $\boldsymbol{m}$ corresponding to the weighted error below the error bound, as a minimized model parameter.
2. In the modeling step of claim 1, the physical property is selected from the group comprising: a velocity of sound propagation, density, permeability, porosity, resistivity, permittivity, Young's modulus, a component of the tensorial stress-strain properties, shear modulus, amount of water present, and amount of oil present.

3. In the modeling step of claim 1, the error bound divided by an initial error $\mathbf{E}_0$ is selected from the group consisting of: below 10^{-5}, below 10^{-6}, below 10^{-7}, and below 10^{-8}.

4. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:
   a) inputting one or more each of *NS* source and *NG* measurement spatial locations;
   b) measuring time domain data at each of the *NG* measurement locations resulting from an input waveform at one of the *NS* source locations propagating through a medium,
      i) for each of the *NS* source locations,
      ii) thereby forming a time domain measurement data set $\boldsymbol{D}_{ji}^{d}(t), \quad (j=1 \sim NG;\ i=1 \sim NS)$, where *d* denotes a data tensor;
   c) Fourier transforming the time domain measurement data set $\boldsymbol{D}_{ji}^{d}(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ having frequency and amplitude information for each of the *NG* measurement locations;
   d) normalizing the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$;
   e) modeling the medium using an iterated model parameter $\boldsymbol{m}$ describing one or more physical properties of the medium,
      (1) the *NS* source and the *NG* measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,
      (2) and initializing the iterated model parameter $\boldsymbol{m}$ with corresponding one or more known bulk properties of the medium being modeled,
      ii) said modeling step comprising:
      iii) creating a measurement model by:
      (1) applying a delta function source collocated with the i^{th} *NS* source,

(2) modeling the response at the *NG* measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}_{ji}^{m}(t)$, m denoting the model response,

(3) repeating the applying and modeling steps at each of the *NS* source locations and *NG* measurement locations until the measurement model is full, and

iv) Fourier transforming the model response $\mathbf{P}_{ji}^{m}(t)$, to obtain a frequency domain synthetic response $\mathbf{P}_{ji}^{m}(\omega)$;

v) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^{m}(\omega) = \mathbf{P}_{ji}^{m}(\omega)\left[\mathbf{P}_{1i}^{m}(\omega)\right]^{-1}$; and

f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$ of the response of the medium, to a level below an error bound,

i) said weighted error met by using the iterated model parameter $\boldsymbol{m}$, known as the a minimized model parameter $\boldsymbol{m}$.

5. The method of claim 4 wherein the modeled normalized wavefield $\mathbf{T}_{ji}^{m}(\omega)$ is independent of the input waveform applied to any of the *NS* source locations.

6. The method of claim 4 further comprising the step of:

   a) storing the minimized model parameter $\boldsymbol{m}$ in a computer-readable medium.

7. The method of claim 4 further comprising the steps of:

   a) displaying the minimized model parameter $\boldsymbol{m}$ as a graphical representation of one or more of the physical properties of the medium measured,

   b) storing an output image represented by the minimized model parameter $\boldsymbol{m}$ in a computer-readable medium.

8. The method of claim 4 further comprising the step of;

   a) storing as a computer program in at least one computer-readable medium,

   b) said steps of claim 4.

9. The method of claim 4 wherein said weighted error results from a weighing matrix $\mathbf{W}_d$ that is an inverse of the standard deviation of the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$.

10. The method of normalized waveform inversion of claim 9 wherein said minimizing step weighted error $\phi(\boldsymbol{m})$ is calculated by a root mean square of the weighing matrix $\mathbf{W}_d$ multiplied by the difference between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$, or $\phi(\boldsymbol{m}) = \left\| \mathbf{W}_d \left(\mathbf{T}_{ji}^{m}(\omega) - \mathbf{T}_{ji}^{d}(\omega) \right) \right\|^2$ summed over all frequencies, *i* sources, and *j* receivers.

11. The method of claim 4 wherein said normalization step is further comprised of the steps of:

    a) choosing one of the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ at one of the measurement locations, such as $\mathbf{D}_{1i}^{d}(\omega)$,

        (1) said chosen measurement spectral data set $\mathbf{D}_{1i}^{d}(\omega)$ known as a reference measurement;

        ii) dividing the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ amplitude at a particular frequency in the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$,

        iii) by the amplitude of the reference measurement $\mathbf{D}_{1i}^{d}(\omega)$ at the same frequency,

    b) to create a normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$.

12. The method of claim 4 wherein the error bound of the minimizing step is calculated by first assigning an initial error $\mathbf{E}_0$, then dividing each subsequent iterated error bound by the initial error $\mathbf{E}_0$.

13. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:

    a) inputting one or more each of *NS* source and *NG* measurement spatial locations;

b) measuring time domain data at each of the *NG* measurement locations resulting from an input waveform at one of the *NS* source locations propagating through a medium,

   i) for each of the *NS* source locations,

   ii) thereby forming a time domain measurement data set

   $\boldsymbol{D}_{ji}^{d}(t), \quad (j = 1 \sim NG;\ i = 1 \sim NT)$, where d denotes a data tensor;

c) Fourier transforming the time domain measurement data set $\boldsymbol{D}_{ji}^{d}(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ having frequency and amplitude information for each of the *NG* measurement locations;

d) normalizing the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$;

e) modeling the medium using an iterated model parameter $\boldsymbol{m}$ describing one or more physical properties of the medium,

   the *NS* source and the *NG* measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,

   and initializing the iterated model parameter $\boldsymbol{m}$ with corresponding one or more known bulk properties of the medium being modeled,

   said modeling step comprising:

   i) creating a measurement model by:

      (1) applying a delta function source collocated with the i^{th} *NS* source,

      (2) modeling the response at the *NG* measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}_{ji}^{m}(t)$, m denoting the model response,

      (3) repeating the applying and modeling steps at each of the *NS* source locations and *NG* measurement locations until the measurement model is full, and

   ii) Fourier transforming the model response $\mathbf{P}_{ji}^{m}(t)$, to obtain a frequency domain synthetic response $\mathbf{P}_{ji}^{m_k}(\omega)$;

iii) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^{m}(\omega) = \mathbf{P}_{ji}^{m}(\omega)\left[\mathbf{P}_{1i}^{m}(\omega)\right]^{-1}$; and

f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$ of the response of the medium, to a level below an error bound,

g) said weighted error met by using the iterated model parameter $\boldsymbol{m}$, known as the a minimized model parameter $\boldsymbol{m}$.

14. The method of claim 13 further comprising the step of;

a) storing as a computer program in at least one computer-readable medium,

i) said steps of claim 13.

15. An article of manufacture for normalized waveform inversion using a computer, said article comprising:

a computer readable medium comprising instructions for a computer to execute, said execution comprising the steps of:

a) inputting one or more each of *NS* source and *NG* measurement spatial locations;

b) measuring time domain data at each of the *NG* measurement locations resulting from an input waveform at one of the *NS* source locations propagating through a medium,

i) for each of the *NS* source locations,

ii) thereby forming a time domain measurement data set $\boldsymbol{D}_{ji}^{d}(t), \quad (j = 1 \sim NG;\ i = 1 \sim NS)$, where d denotes a data tensor;

c) Fourier transforming the time domain measurement data set $\boldsymbol{D}_{ji}^{d}(t)$ to create a measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ having frequency and amplitude information for each of the *NG* measurement locations;

d) normalizing the measurement spectral data set $\mathbf{D}_{ji}^{d}(\omega)$ to create a normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$;

e) modeling the medium using an iterated model parameter $\boldsymbol{m}$ describing one or more physical properties of the medium,

the *NS* source and the *NG* measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,

and initializing the iterated model parameter $\boldsymbol{m}$ with corresponding one or more known bulk properties of the medium being modeled,

said modeling step comprising:

i) creating a measurement model by:

(1) applying a delta function source collocated with the i^{th} *NS* source,

(2) modeling the response at the *NG* measurement locations, using a time domain modeling method, to create a synthetic medium response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}_{ji}^{m}(t)$, m denoting the model response,

(3) repeating the applying and modeling steps at each of the *NS* source locations and *NG* measurement locations until the measurement model is full, and

ii) Fourier transforming the model response $\mathbf{P}_{ji}^{m}(t)$, to obtain a frequency domain synthetic response $\mathbf{P}_{ji}^{m}(\omega)$;

iii) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^{m}(\omega) = \mathbf{P}_{ji}^{m}(\omega)\left[\mathbf{P}_{1i}^{m}(\omega)\right]^{-1}$; and

f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$ of the response of the medium, to a level below an error bound,

i) said weighted error met by using the iterated model parameter $\boldsymbol{m}$, known as the a minimized model parameter $\boldsymbol{m}$.

16. An iterative method of using normalized waveform inversion to obtain a model parameter describing one or more physical properties of a medium, the method comprising the steps of:

a) inputting one or more each of *NS* source and *NG* measurement spatial locations;

b) measuring time domain data at each of the *NG* measurement locations resulting from an input waveform at one of the *NS* source locations propagating through a medium,

   i) for each of the *NS* source locations,

   ii) thereby forming a time domain measurement data set

   $\boldsymbol{D}^d_{ji}(t), \quad (j = 1 \sim NG;\ i = 1 \sim NS)$, where *d* denotes a data tensor;

c) Fourier transforming the time domain measurement data set $\boldsymbol{D}^d_{ji}(t)$ to create a measurement spectral data set $\mathbf{D}^d_{ji}(\omega)$ having frequency and amplitude information for each of the NG measurement locations;

d) normalizing the measurement spectral data set $\mathbf{D}^d_{ji}(\omega)$ to create a normalized data wavefield $\mathbf{T}^d_{ji}(\omega)$;

e) modeling the medium using an iterated model parameter $\boldsymbol{m}$ describing one or more physical properties of the medium,

   the *NS* source and the *NG* measurement spatial locations used as respective model input and model response spatial locations contained within the model of the medium,

   and initializing the iterated model parameter $\boldsymbol{m}$ with corresponding one or more known bulk properties of the medium being modeled,

   said modeling step comprising:

   i) creating a measurement model by:

      (1) applying a delta function source collocated with the i^{th} source,

      (2) modeling the response at the *NG* measurement locations, using a frequency domain modeling method, to create a **frequency domain** synthetic response at the j^{th} receiver due to the i^{th} source, $\mathbf{P}^m_{ji}(\omega)$, $\boldsymbol{m}$ denoting the model response,

      (3) repeating the applying and modeling steps at each of the *NS* source locations and *NG* measurement locations until the frequency domain synthetic response is full, and

ii) forming a normalized modeled wavefield using the frequency domain synthetic response $\mathbf{T}_{ji}^{m}(\omega) = \mathbf{P}_{ji}^{m}(\omega)\left[\mathbf{P}_{1i}^{m}(\omega)\right]^{-1}$; and

f) minimizing a weighted error, between the normalized data wavefield $\mathbf{T}_{ji}^{d}(\omega)$ and the normalized modeled wavefield $\mathbf{T}_{ji}^{m}(\omega)$ of the response of the medium, to a level below an error bound,

i) said weighted error met by using the iterated model parameter $\boldsymbol{m}$, known as the a minimized model parameter $\boldsymbol{m}$.

17. The method of claim 16 further comprising the step of;

a) storing as a computer program in at least one computer-readable medium, said steps of claim 16.

18. An article of manufacture for normalized waveform inversion using a computer, said article comprising: a computer readable medium comprising instructions for a computer to execute, said execution comprising the steps of claim 16.